Welcome

Low Density Supersonic Decelerator Design Verification Test Dynamics: Damping Assessment and Vibration Mitigation

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352L Spacecraft Structures and Dynamics
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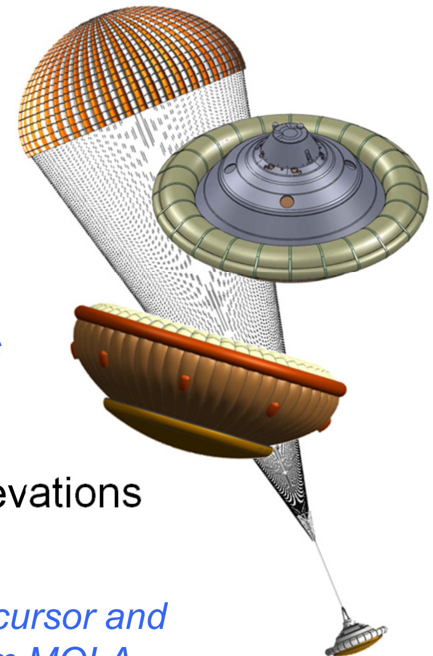
Low Density Supersonic Decelerator

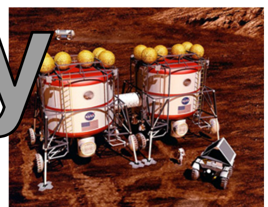


What

Develop new supersonic inflatable decelerator and supersonic parachute technologies to TRL-6

- ➔ *6 and 8-meter diameter Mach 3.5 inflatable decelerators*
- ➔ *33.5-meter diameter Mach 2+ supersonic ringsail parachute with non-mortar deployment*

Why



Artist's Concept

Enable sending larger payloads to higher elevations on Mars, with greater precision

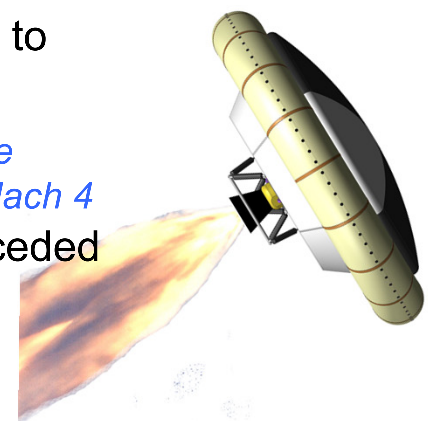
- *2 to 2.7 metric tons for science and human precursor and cargo missions, km's to meters precision, +1 km MOLA*
- *Pave the way for technology development for human missions*

How

Fly them in Earth's stratosphere at supersonic speeds to simulate operation in the thin air of Mars

- ➔ *A high-altitude balloon lofts ~3200 kg vehicle with full-scale devices to ~36 km — rocket fires to send it to ~50 km at Mach 4*

When



In 2013 and 2014, four such flights would be preceded by low-altitude tests in 2011-2013

- *First rocket sled tests of inflatables in August 2012*
- *First parachute sled tests in June 2013*

How Much

Total cost of approximately $180M over FY12-15

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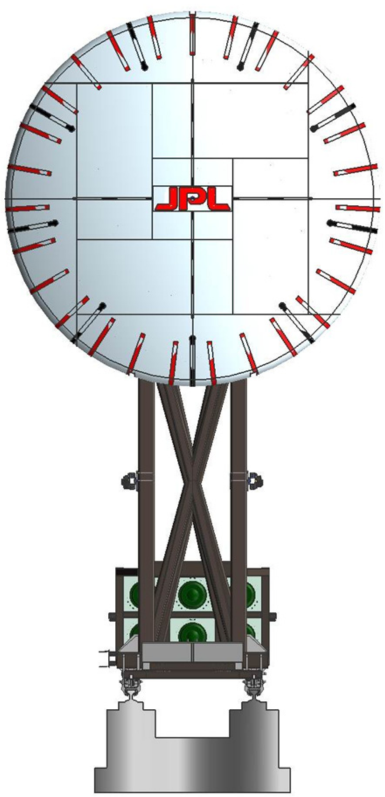
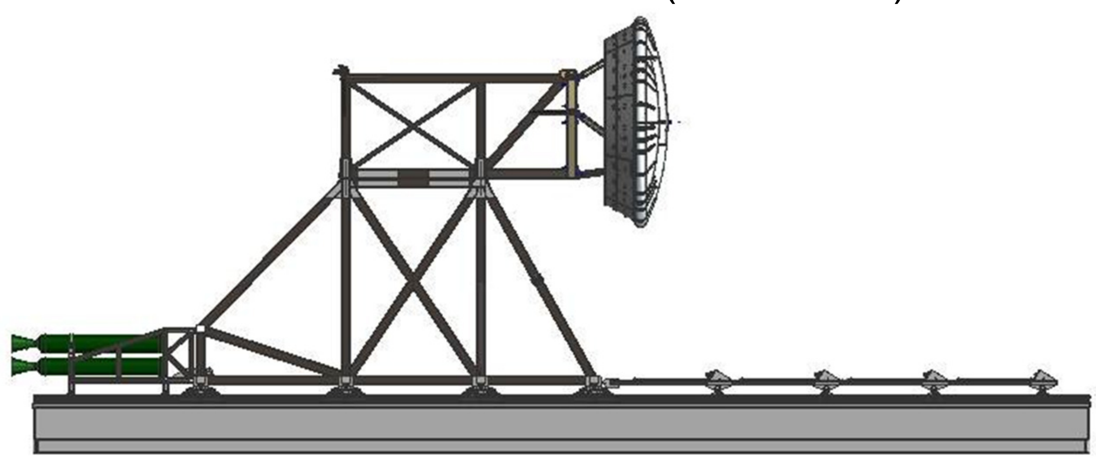
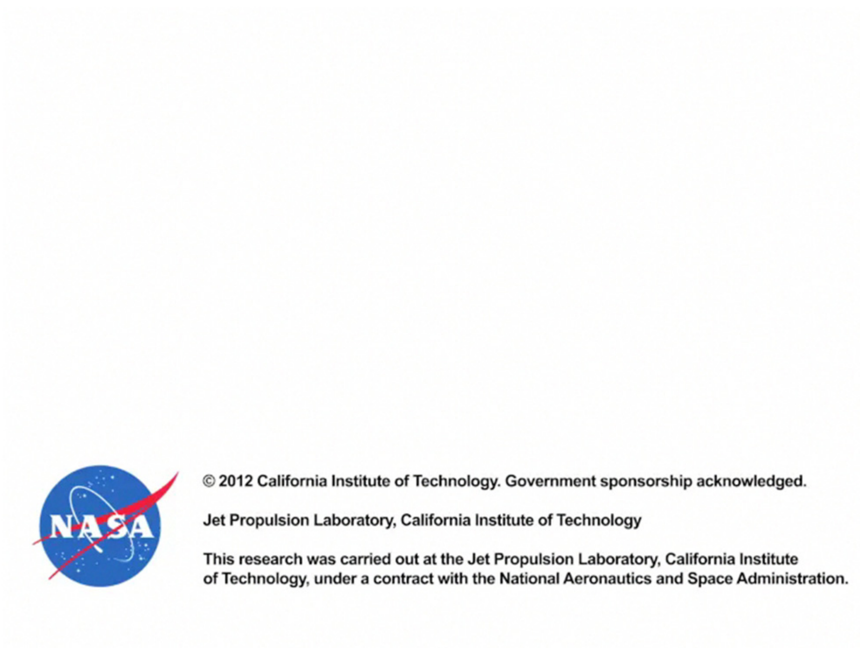
Design Verification Tests



- Aerodynamic loading but *not* Mach is replicated to test the strength and operation of the devices
    - Allows over-testing of strength which is not feasible for at-Mach testing
    - Lower cost tests to assure working devices before at-Mach testing
- Supersonic Inflatable Aerodynamic Decelerator (SIAD) Hardware mounted on rocket sled (China Lake)



Test Videos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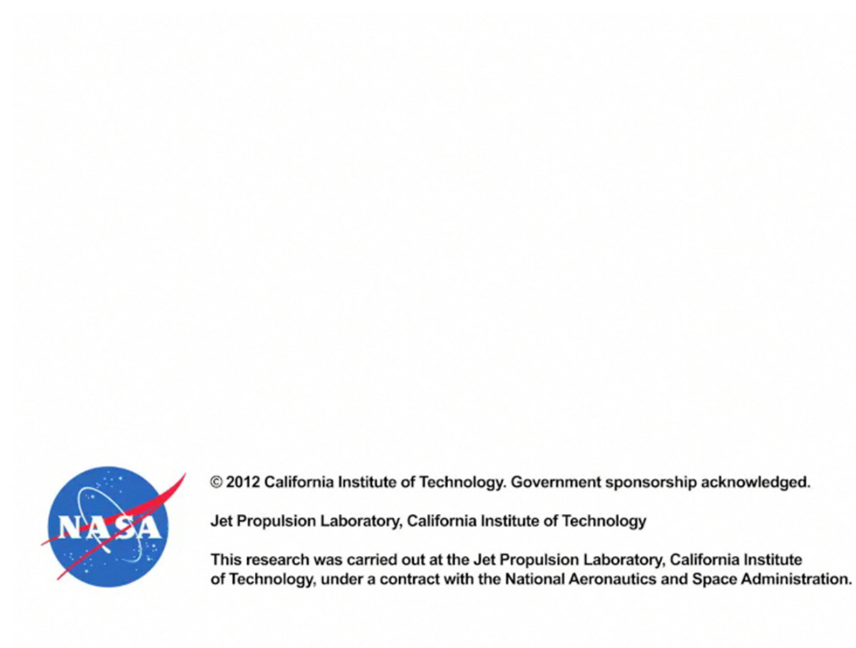
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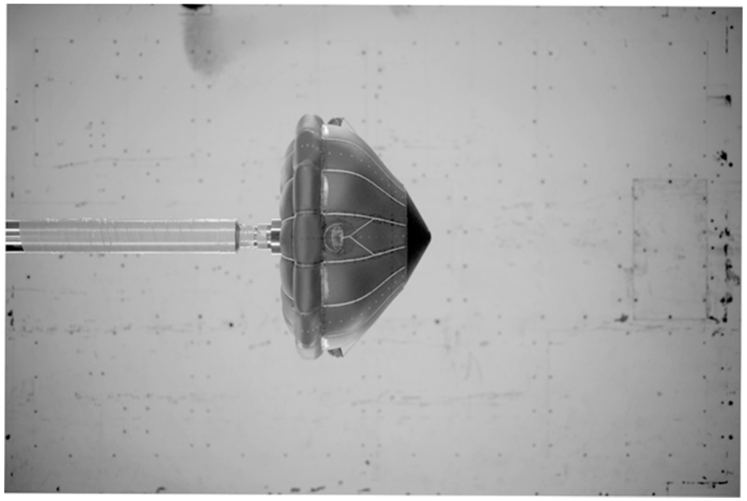
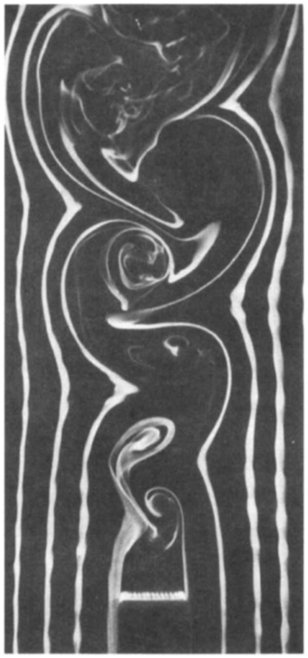
Vortex Shedding Concern



- Vortex shedding is an unsteady flow that takes place in certain flow regimes
  - Caused when fluid flows past a blunt object
  - Vortices are created at the back of the body and detach periodically from either side
  - *As vortices are shed the pressure distribution varies and periodic lateral forces are created on the body*



- ***What is the effect of vortex shedding dynamic loading on the test hardware as it travels along the sled?***

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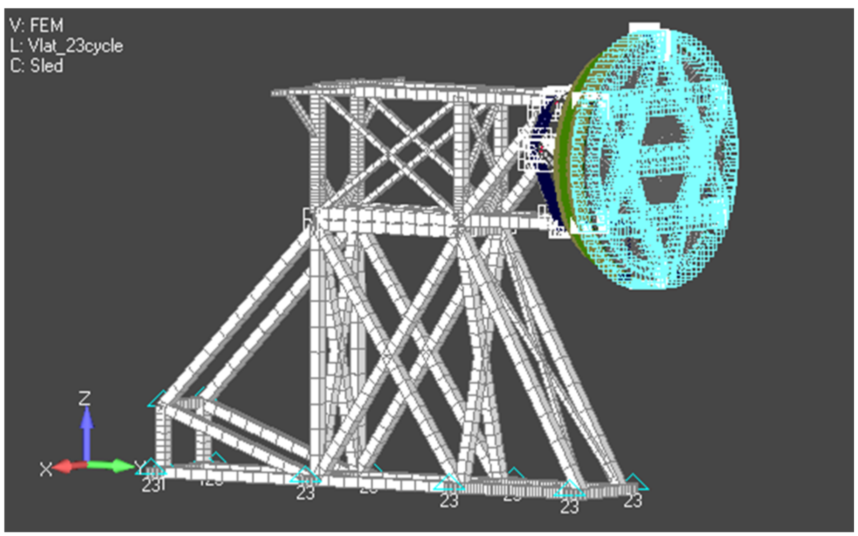
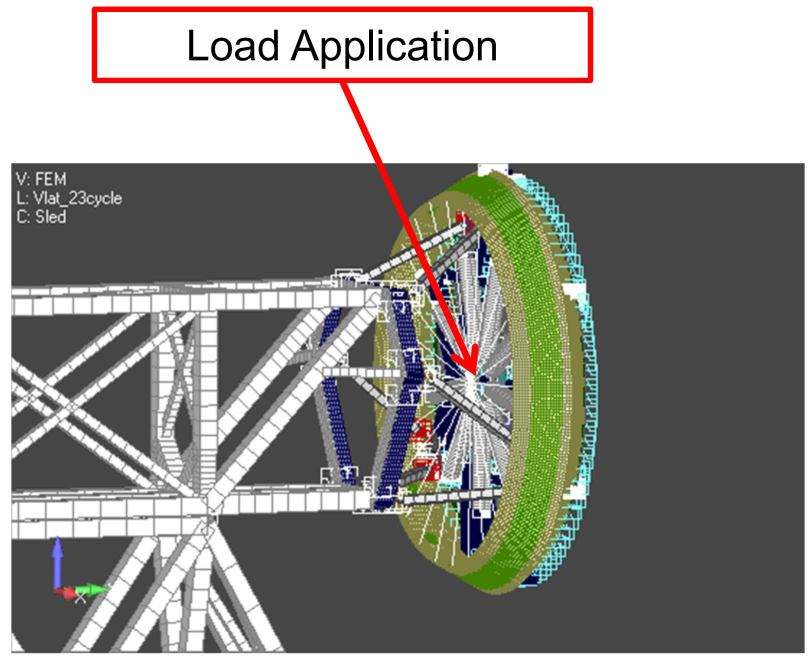
Vortex Shedding Analysis

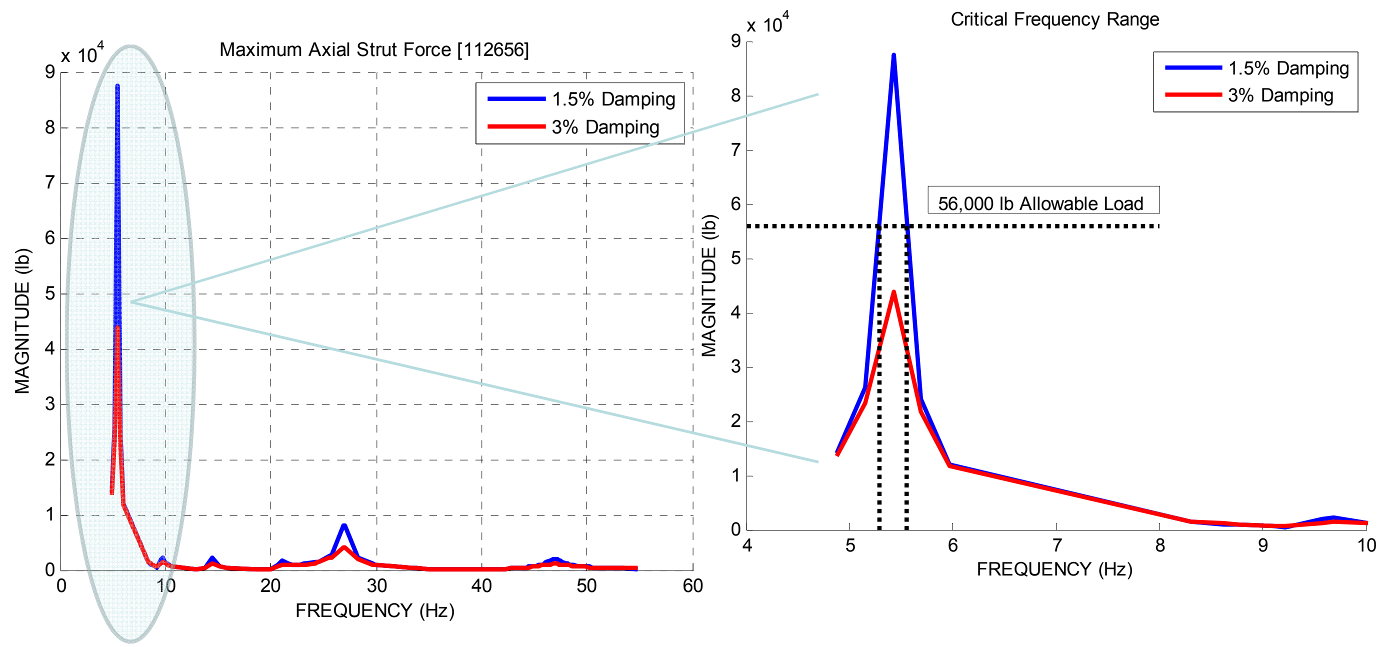
- Conservative peak lateral load due to vortex shedding → V_x=*0.13*p*A*
  - *p* = front pressure load from aerodynamics
  - *A* = projected frontal area of the vehicle
- Model was constrained at 8 nodes representing sliders in vertical and lateral DOF and at 4 nodes in axial DOF
- Load was applied to the node representing center of pressure of the SIAD and transferred to the vehicle body through RBE3 element





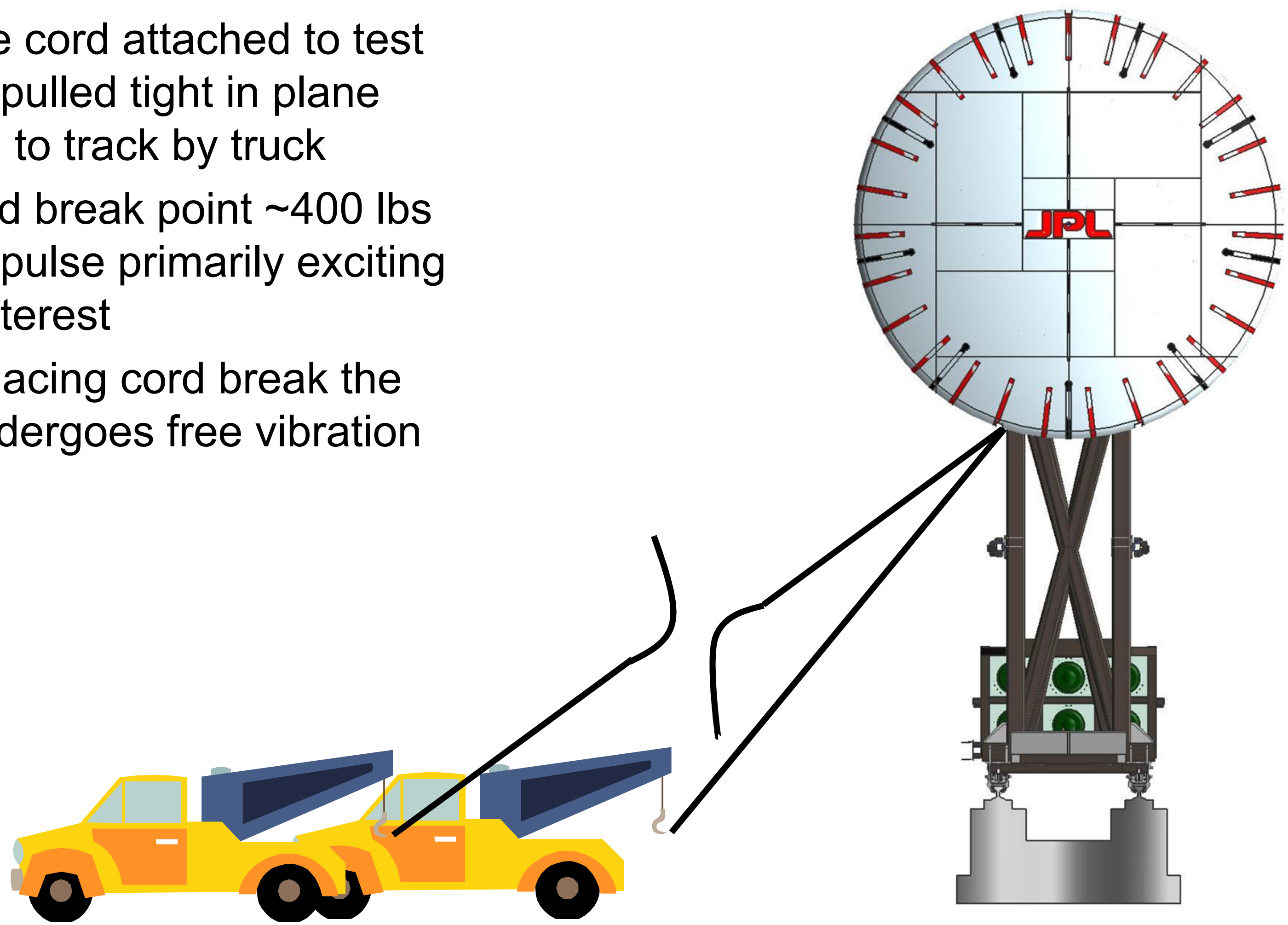
Frequency Response due to Vortex Shedding

- Remark 1: Dominant 1st mode behavior at 5.426 Hz
- Remark 2: Critical frequency range [5.287,5.561] Hz is established with respect to strut allowable load
- M.S. for Struts: -0.36 (1.5 % Damping), 0.28 (3 % Damping)
- *Project elected to perform damping "Pull Test" to investigate further the damping of the test setup*



Damping from Pull Test

- Kevlar lace cord attached to test setup and pulled tight in plane orthogonal to track by truck
- Lacing cord break point ~400 lbs created impulse primarily exciting mode of interest
- Following lacing cord break the system undergoes free vibration



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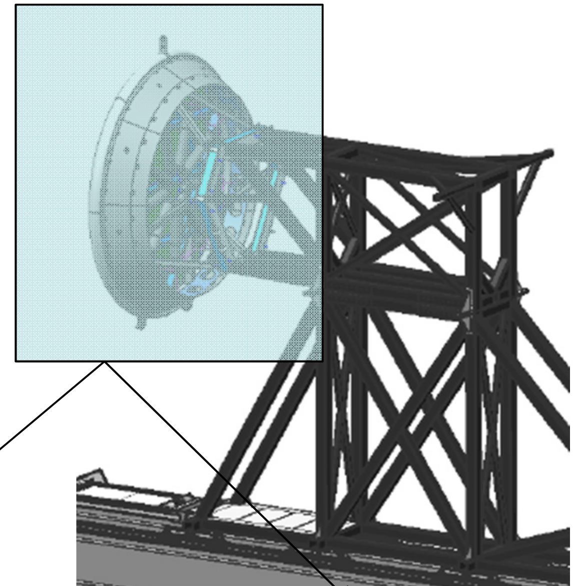
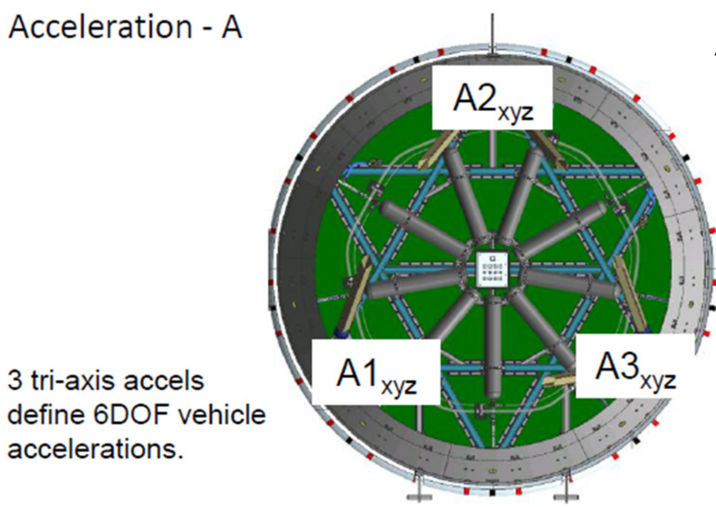
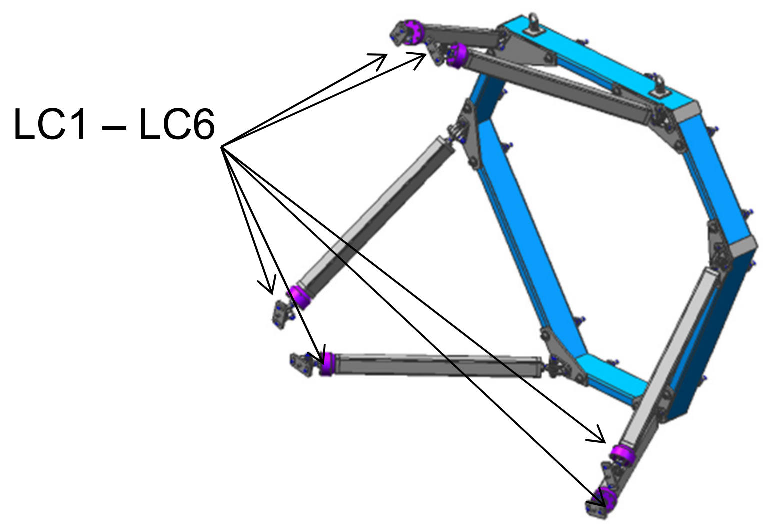
Damping from Pull Test: Data Acquisition

- Real time data analyzed from sensors placed on test hardware at the following locations:
  - *Tri-axial accelerometers placed in the configuration shown on*
  - *Load cells placed at struts connecting the SIAD to strong back*



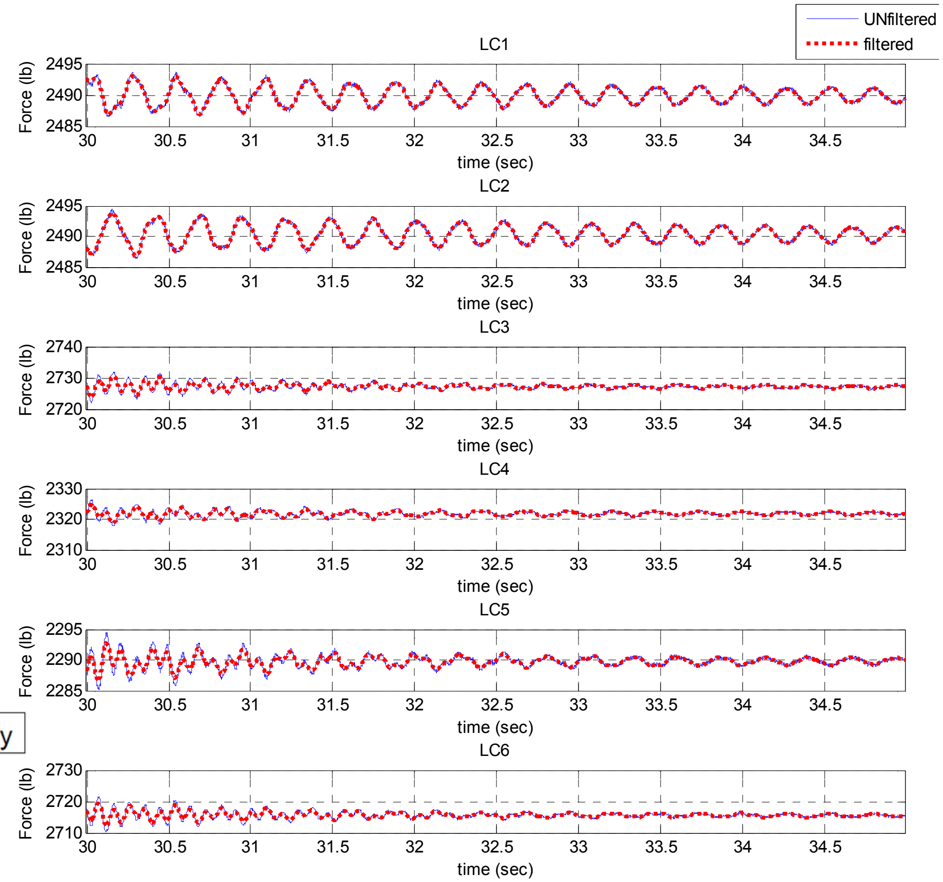


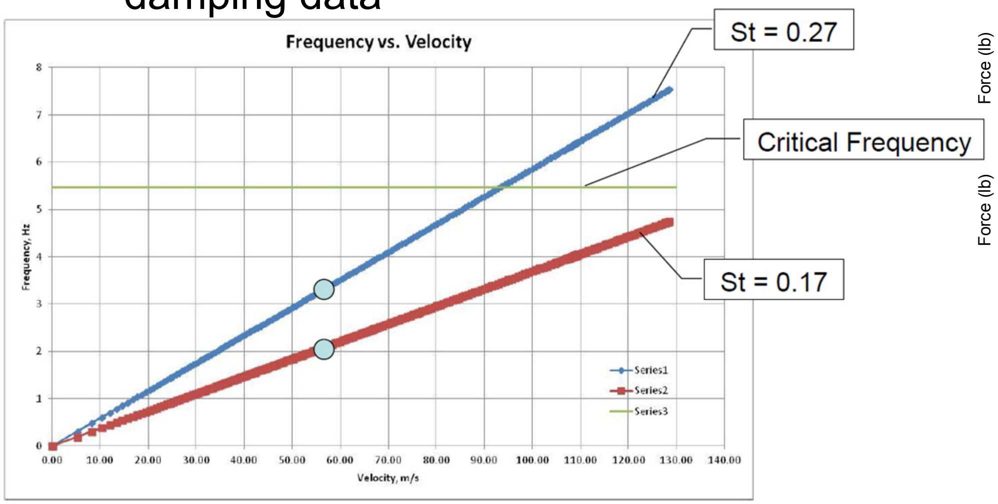


Damping from Slow Speed Test

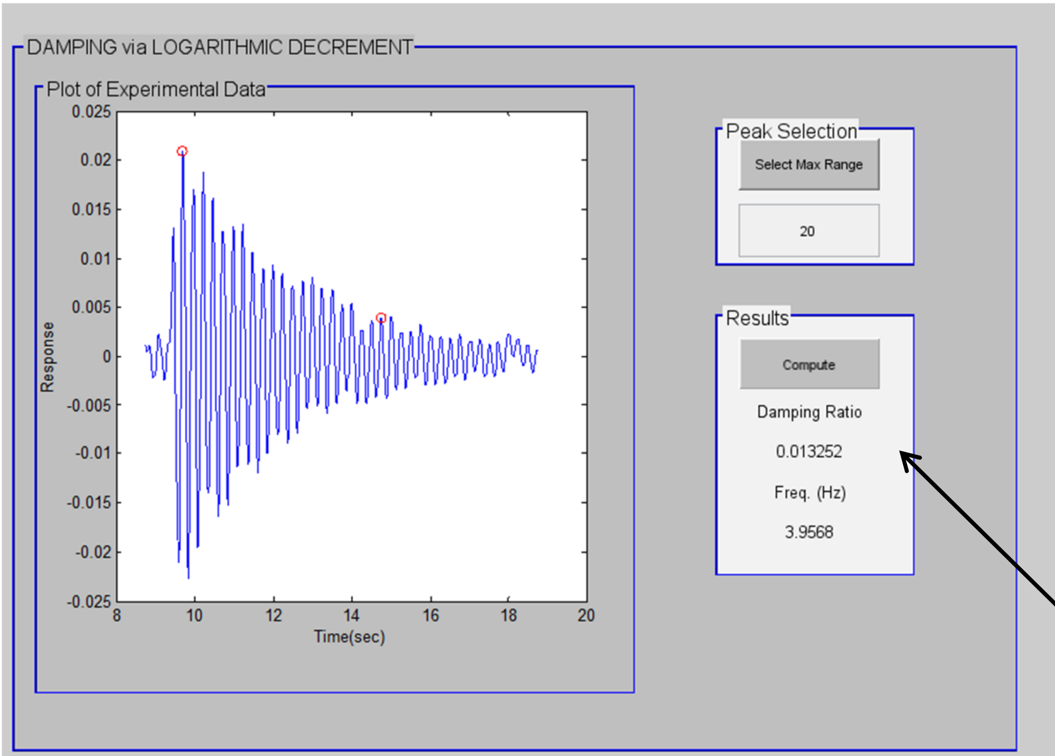
- It was determined that a slow speed test would not excite the critical mode lateral mode of 5.42 Hz
- Data acquisition identical to pull test
- Slow speed test contained more realistic slipper-to-track boundary condition
- Used as verification of pull test damping data

Free vibration portion of the load cell data from slow speed test with filtering at 12 Hz





Damping Summary and Recommendation



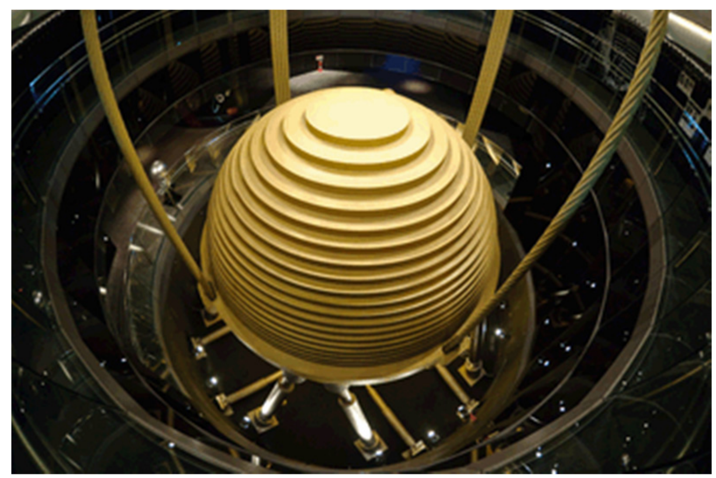
Example damping calculation for A3-X, Ch. 36, (20 cycles between peaks) from pull test

Damping Summary			
Load Cells		Accelerometers	
LC1	1.33	A1-X	1.33
LC2	1.35	A2-X	1.27
LC3	1.44	A3-X	1.33
LC4	1.23		
LC5	1.4		
LC6	1.28		
Ave	1.34		1.31

- Damping determined via logarithmic decrement method: $\zeta = \frac{1}{2\pi j} ln \frac{u_j}{u_{i+j}}$
- Data filtered to remove high frequency noise
- *After analyzing damping from test data, a 'Plan B' for Installing a damping device to achieve minimum 3 % of critical damping was developed should vortex shedding loads be an issue for higher speed test*

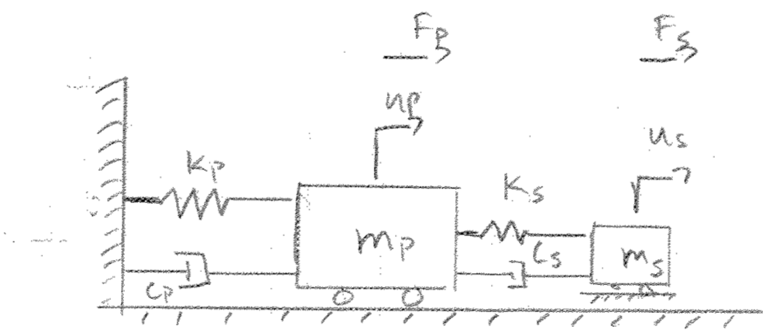
Tuned Mass Damper (TMD) Background

- Large masses have been used to absorb vibration due to external excitation in large buildings since 1976 (John Hancock Tower, Boston, MA)
- One of the largest TMDs is 730 tons (Taipei 101, Taipei, Taiwan) and harmonically absorbs vibration due to wind excitations using a massive swinging pendulum
- *Effective in reducing base excitation* due to ground motion



TMD Feasibility Study

- Approximate the LDSD test setup as a SDOF lumped mass with a smaller tuned mass damper
- Total Weight of test assembly: Mp ~ 34,000 lb
- Stiffness of SDOF inferred from first mode → fp = 5.42 Hz
- Assume damping of SDOF ζp = 1.5%



$$\begin{Bmatrix} \dot{u}_p \\ \dot{u}_r \\ \ddot{u}_p \\ \ddot{u}_r \end{Bmatrix} = \underbrace{\begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\omega_p^2 & +\mu\omega_s^2 & -2\zeta_p\omega_p & +2\mu\zeta_s\omega_s \\ +\omega_p^2 & -\omega_s^2(1+\mu) & +2\zeta_p\omega_p & -2\zeta_s\omega_s(1+\mu) \end{bmatrix}}_{A} \begin{Bmatrix} u_p \\ u_r \\ \dot{u}_p \\ \dot{u}_r \end{Bmatrix} + \underbrace{\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{m_p} & 0 \\ -\frac{1}{m_p} & \frac{1}{m_s} \end{bmatrix}}_{E} \begin{bmatrix} F_p \\ F_s \end{bmatrix}$$

Where state space form is:

$$\tilde{y} = \tilde{C}\,\tilde{x} + \tilde{D}\,\hat{F}$$

$$\dot{\tilde{x}} = \tilde{A}\,\hat{x} + \tilde{E}\,\hat{F}$$

$$\tilde{x} = \begin{Bmatrix} u_p \\ u_r \\ \dot{u}_p \\ \dot{u}_r \end{Bmatrix}$$

$$\begin{Bmatrix} \ddot{u}_p \\ \ddot{u}_r \end{Bmatrix} = \underbrace{\begin{bmatrix} -\omega_p^2 & \mu\omega_s^2 & -2\zeta_p\omega_p & 2\mu\zeta_s\omega_s \\ \omega_p^2 & -\omega_s^2(1+\mu) & 2\zeta_p\omega_p & -2\zeta_s\omega_s(1+\mu) \end{bmatrix}}_{\tilde{C}} \begin{Bmatrix} u_p \\ u_r \\ \dot{u}_p \\ \dot{u}_r \end{Bmatrix} + \underbrace{\begin{bmatrix} \frac{1}{m_p} & 0 \\ -\frac{1}{m_p} & \frac{1}{m_s} \end{bmatrix}}_{\tilde{D}} \begin{Bmatrix} F_p \\ F_s \end{Bmatrix}$$

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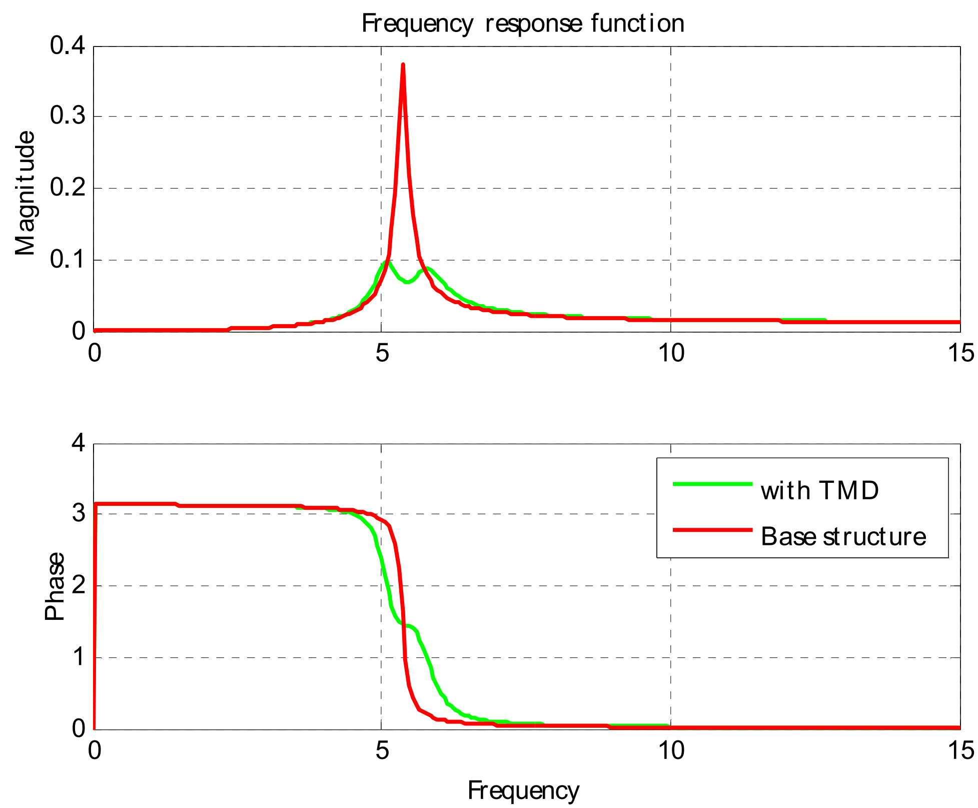
SDV TMD Feasibility Study Results

- Ratio of TMD mass to Test Setup mass, μ, not to exceed 2% → Ms ~ 700 lbs
- Assume TMD damping, ζs = 5%
- TMD in feasibility study designed to control mode at 5.42 Hz ($\omega s \sim \omega p$)
- > 50% reduction in first mode amplitude (for unit impulse) observed from transfer function plot
- Major peak is split into 2 separate peaks indicating addition of 2nd mode



$$H(i\omega) = \frac{Y(i\omega)}{F(i\omega)} = C(sI-A)^{-1}E + D \Big|_{s=i\omega}$$

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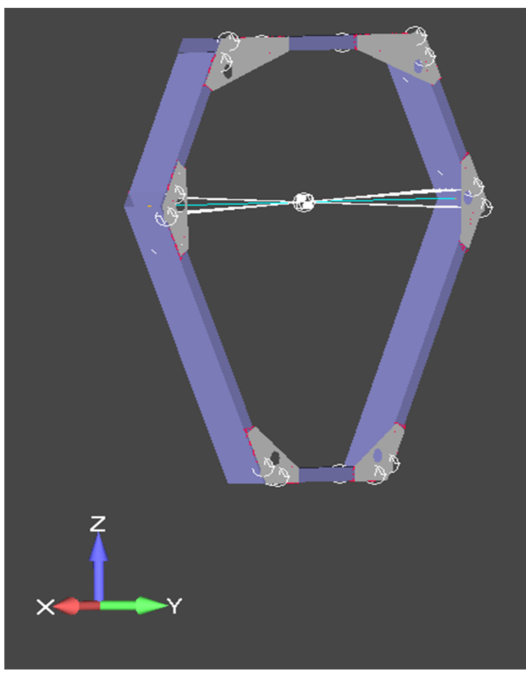
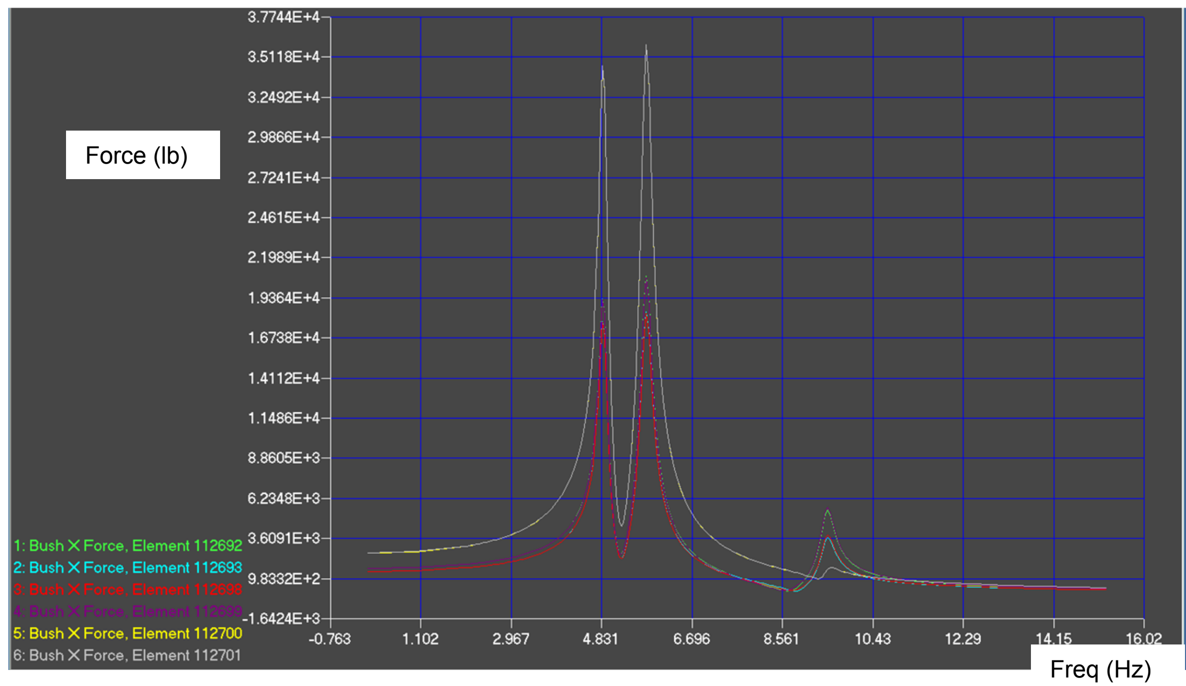
TMD Transient Simulation

- CONM3 allowed to oscillate in lateral direction between strong back of sled
- Observed reduction in frequency response well below buckling allowable loads of struts





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Conclusion

- For a worst case vortex shedding load, structural damping < 3% poses risk to the SDV test campaign at high speeds
- Both pull test data and slow speed test data show first mode damping to be ~ 1.3 %
- A feasibility study for adding a Tuned Mass Damper - 2% of the total mass of the SDV test setup – show favorable reductions of peak loading > 50 %
- Feasibility study was confirmed by simulating the addition of the TMD to the SDV FEM. The forces calculated in the strut did not exceed buckling allowables for the closed loop lightly damped system (~1.5%).

Epilogue

- Due to large uncertainty in assessing parameters related to the aerodynamic forces on a blunt body (lack of experimental data, Strouhal number, drag coefficient, etc.) vortex shedding loads turned out not to be a significant driver for the SIAD Design Verification portion of the LDSD test program
- SDV tests were performed successfully without implementation of Tuned Mass Damper
- ‘Plan B’ TMD strategy did assist test readiness review to demonstrate that schedule would not be halted should large vortex shedding loads be observed

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